Photon assisted electric field domains in doped semiconductor superlattices

Ramón Aguado and Gloria Platero

Instituto de Ciencia de Materiales (CSIC) Cantoblanco,28049 Madrid, Spain.

(3 December 1997)

Abstract

We study photon-assisted tunneling (PAT) through weakly-coupled doped semiconductor superlattices (SL's) in the high voltage regime. A self-consistent model which treats the Coulomb interaction in a mean field approximation is considered. We discuss the formation of electric field domains in the presence of THz radiation and the appearance of new multistability regions caused by the combined effect of the strong non linearity coming from the Coulomb interaction and the new PAT channels. We show how the electric field domains can be supported by the virtual photonic sidebands due to multiple photon emission and absorption.

Keywords: Superlattices, Photon-Assisted Tunneling, Electric Field Domains.

Ramon Aguado, ICMM(CSIC), Cantoblanco 28049, Madrid, Spain.

Fax: 34-1-3720623, e-mail: raguado@everest.icmm.csic.es

Recently, the transport properties of semiconductor nanostructures in the presence of AC fields have been the subject of interest [1–3]. Among the experiments based on the response of a nanostructure to an AC field one might consider PAT, electron pumps, turnstiles, and others . On the other hand the transport properties having their origin in Coulomb interaction have attracted a great deal of attention in recent times. In weakly-coupled SL's, multistability, electric field domain formation, self-sustained current oscillations and chaos have been much studied [4,5]. In this work we deal with PAT in weakly-coupled doped SL's whose transport mechanism is sequential tunneling. In this regime the intrinsic miniband width is typically one order of magnitude smaller than the scattering induced broadening (for the samples we are going to analyze the miniband width is $\sim 0.1meV$). In this case the miniband transport can be neglected and the transport at low bias voltages is governed by sequential resonant tunneling from ground state to ground state in adjacent wells. The PAT through a SL in the low bias regime, where the non linear effects of the Coulomb interaction are small, has been explored both experimental [1] and theoretically [6]. In this regime, and for certain values of the intensity and frequency of the AC field, the sample can exhibit negative conductance [1,6]. Here, we concentrate in the high bias regime where the Coulomb interaction has to be considered in order to discuss electric field domains formation in the presence of THz fields. We study the formation of new multistability regions induced by the AC field and we show how the electric field domains can be supported by the virtual PAT sidebands [7]. An extension of the model of Ref. 10 is put forward in order to account for the effect of an AC field on the I–V curve of a doped SL. The model assumes that the characteristic time of intersubband relaxation is shorter than the tunneling time and then that only the ground state of each quantum well is populated. In order to model relaxation in the transport direction due to scattering , we assume that the spectral functions in the wells are Lorentzians. Relaxation in the planes perpendicular to the transport is taken into account by imposing current conservation through the whole structure that will determine the sequential current as well as the Fermi energies within each well. The assumption of having Fermi distribution functions in the wells implies some scattering mechanism that

thermalizes the electrons towards an equilibrium state [8]. If there is no mechanism for obtaining thermal equilibrium the nonequilibrium transport must be treated with a suitable quantum kinetic technique (for example the Keldysh technique [3]).

The currents are calculated by means of the Transfer Hamiltonian method (TH) that consists in connecting by time dependent perturbation theory the different parts of the structure (decoupled in the remote past) by tunneling matrix elements [9].

The effect of the AC field is included in the single particle energies in the different isolated regions of the structure (leads and wells); $\epsilon_i(t) = \epsilon_i + eV_i(t)$ before the tunneling couplings are switched on [3]. Due to this time dependence the single particle propagators acquire phase factors. The noninteracting retarded Green's function at the i-th region becomes:

$$g_i^r(t,t') \equiv -\frac{i}{\hbar}\theta(t-t')\langle\{\mathbf{c}_{k_i}(t), \mathbf{c}_{k_i}^\dagger(t')\}\rangle = -\frac{i}{\hbar}\theta(t-t')e^{[-\frac{i}{\hbar}\int_{t'}^{t} d\tau\epsilon_i(\tau)]}$$
$$= \sum_{n,m=-\infty}^{\infty} J_n(\frac{eV_i}{\hbar\omega})J_m(\frac{eV_i}{\hbar\omega})e^{-\frac{i}{\hbar}\epsilon_i(t-t')}e^{-in\omega t}e^{im\omega t'}. \quad (1)$$

In this expression J_n is the Bessel function of first kind and the time dependent voltage is $V_i(t) = V_i \cos\omega t$. Following the TH method we obtain the transmission probability from the i-th well to the $i+1$-th well , from the emitter to the first well and from the N-th well (N is the number of wells) to the collector. From the transmission probability we evaluate the time averaged sequential current . The interwell current is [6]:

$$J_{i,i+1} = \frac{2e\hbar k_BT}{\pi^2 m^*}\sum_{j=1}^{n_{max}}\sum_{m=-\infty}^{\infty} J_m^2(\frac{eFd}{\hbar\omega})\int \frac{\gamma}{[(\epsilon-\epsilon_{C1}^i)^2+\gamma^2]}\frac{\gamma}{[(\epsilon-\epsilon_{Cj}^{i+1}+m\hbar\omega)^2+\gamma^2]}$$
$$\times\, T_{i+1}(\epsilon,\epsilon+m\hbar\omega)ln[\frac{1+e^{\frac{(\epsilon_{\omega_i}-\epsilon)}{k_BT}}}{1+e^{\frac{(\epsilon_{\omega_{i+1}}-\epsilon-m\hbar\omega)}{k_BT}}}]d\epsilon, \quad (2)$$

where ϵ_{Cj}^i is the j-th resonant state of the i-th well (n_{max} is the number of subbands participating in the transport) , $T_i(\epsilon, \epsilon+m\hbar\omega)$ is the inelastic transmission through the i-th barrier. In the argument of the Bessel functions , $Fd = V_{i+1} - V_i$ is the potential drop between the i-th well and the $i+1$-th well due to the time dependent field; F the intensity of the time dependent external field and d the period of the SL. The current from the emitter to the first well, $J_{0,1}$, and the one from the N-th well to the collector, $J_{N,N+1}$, are also derived in

our model. The electrons in each well are in local equilibrium with Fermi energies ϵ_{ω_i} which define the charge densities n_i. For a given set of variables $\{\epsilon_{\omega_i}\}$ and in the stationary regime the currents have to fulfill the set of equations [10]:

$$J_{i-1,i} - J_{i,i+1} = 0 \qquad\qquad i = 1, \ldots, N. \tag{3}$$

Here $J_{i,i+1} = J_{i,i+1}(\epsilon_{\omega_i}, \epsilon_{\omega_{i+1}}, \Phi)$, $J_{0,1} = J_{0,1}(\epsilon_{\omega_1}, \Phi)$, and $J_{N,N+1} = J_{N,N+1}(\epsilon_{\omega_N}, \Phi)$. Φ denotes the set of non linear voltage drops (potential drops at the accumulation and depletion layers, barriers and wells) through the structure caused by the accumulation of charge densities n_i in the wells. These potential drops as well as all the quantities in the problem are calculated self-consistently for each applied voltage including the Coulomb interaction in a mean field approximation [10]. Our numerical procedure allows us to obtain both the stable and unstable solutions as well as all the multistability regions in the I–V curve.

In Fig. 1 we plot the I–V curve of a SL consisting in 10 wells with 90$\mathring{A}$GaAs wells and 40$\mathring{A}$$Ga_{0.5}Al_{0.5}As$ barriers. The doping at the leads is $N_D = 2 \times 10^{18}\mathrm{cm}^{-3}$ and in the wells it is $N_D^w = 1.5 \times 10^{11}\mathrm{cm}^{-2}$, the half-width of the resonant states is $\gamma = 2$meV and T=0.

After the initial peak which is determined by C1–C1 sequential tunneling (C_j are the resonant states of the wells ordered starting from the ground state) through the whole SL the current evolves along a series of branches (solid lines). This behaviour is explained by the formation of a charge accumulation layer in one of the wells (domain wall) [4,5] that splits the SL in two regions with low and high electric field respectively (see inset in Fig. 2). Increasing the voltage, this charge cannot move continuously through the SL. This motion can only occur for voltages allowing resonant interwell tunneling, in this situation the domain wall moves from the i-th well to the $i-1$-th well. In the I–V characteristics this process leads to a series of sharp discontinuities (the stable branches are connected by unstable ones, dotted lines in the figure). In the static case, transport in the high electric field domain is only possible by C1–C2 resonances, whereas in the case with AC the resonances occur between the virtual PAT emission sidebands corresponding to the C2 subband in the $i+1$-th well and the PAT absorption sidebands corresponding to the C1 subband in the i-th well .

These processes are shown in Fig. 2 where the I–V curve in the presence of THz radiation ($F = 0.47 \times 10^6$V/m$, \omega = 3$THz) is plotted. In the inset we have depicted the calculated potential profile of the SL for a voltage $V_0 = 0.86$V. The inset shows that the virtual PAT channels can support electric field domains (the dashed lines represent the PAT channels), the blow up shows that the high field domain is supported by C1–C2 tunneling involving absorption of two photons. Increasing the intensity of the AC field to $F = 0.95 \times 10^6$V/m (Fig. 3) the probability of having multiphotonic effects increase, leading to multistability of the branches. The inset shows a magnification of the first branch, the circles mark the stable operating points for a fixed voltage. At $V_1 = 0.16$V transport in the high field domain occurs via tunneling between the two-photon absorption virtual state associated with C1 and the two-photon emission virtual state associated with C2. At $V_2 = 0.19$V the branch develops a multistable solution (five solution coexist, three stable, two unstable). These solutions correspond to a different number of photons emitted in C2: one photon in the highest current stable solution (circle a), two photons in the lowest current stable solution (circle c); the process from the highest current to the lowest one involves the motion of the domain wall. The situation repeats periodically as the domain wall moves, giving the sawtooth structure in the current.

In summary, we have presented and solved a microscopic self-consistent model for the sequential current through a weakly-coupled doped SL in the presence of THz radiation. We have shown how the electric field domains can be supported by the virtual PAT sidebands. For strong THz fields multiphotonic effects lead to appearance of new multistability regions in the I–V curve.

We acknowledge L. L. Bonilla and M. Moscoso for fruitful discussions and collaboration on related topics. This work has been supported by the CICYT (Spain) N0.MAT 94-0982-c02-02.

REFERENCES

[1] B. J. Keay, S. Zeuner, S. J. Allen, K. D. Maranowski, A. C. Gossard, U. Bhattacharya and M. J. W. Rodwell., Phys. Rev. Lett **75** 4102 (1995).

[2] L. P. Kouvenhowen, S. Jauhar, J. Orenstein, P. L. McEuen, Y. Nagamune, J. Motohisa, and H. Sakaki, Phys. Rev. Lett. **73**, 3443 (1994).

[3] Antti-Pekka Jauho, Ned S. Wingreen and Yigal Meir, Phys. Rev. B, **50**, 5528 (1994).

[4] H. T. Grahn, R. J. Haug, W. Müller, and K. Ploog, Phys. Rev. Lett **67** 1618 (1991).

[5] A. Wacker, M. Moscoso, M. Kindelan, and L. L. Bonilla, Phys. Rev. B, **55**, 2266 (1997) and references therein.

[6] Gloria Platero and Ramon Aguado, Appl. Phys. Lett, **70** 3546 (1997).

[7] B. J. Keay, S. J. Allen, Jr., J. Galan, J. P. Kaminski, K. L. Campman, A. C. Gossard, U. Bhattacharya and M. J. W. Rodwell., Phys. Rev. Lett **75** 4098 (1995).

[8] M. Jonson, Phys. Rev B, **39**, 5924 (1989).

[9] R. Aguado, J. Iñarrea and G. Platero , Phys. Rev B, **53**, 10030 (1996).

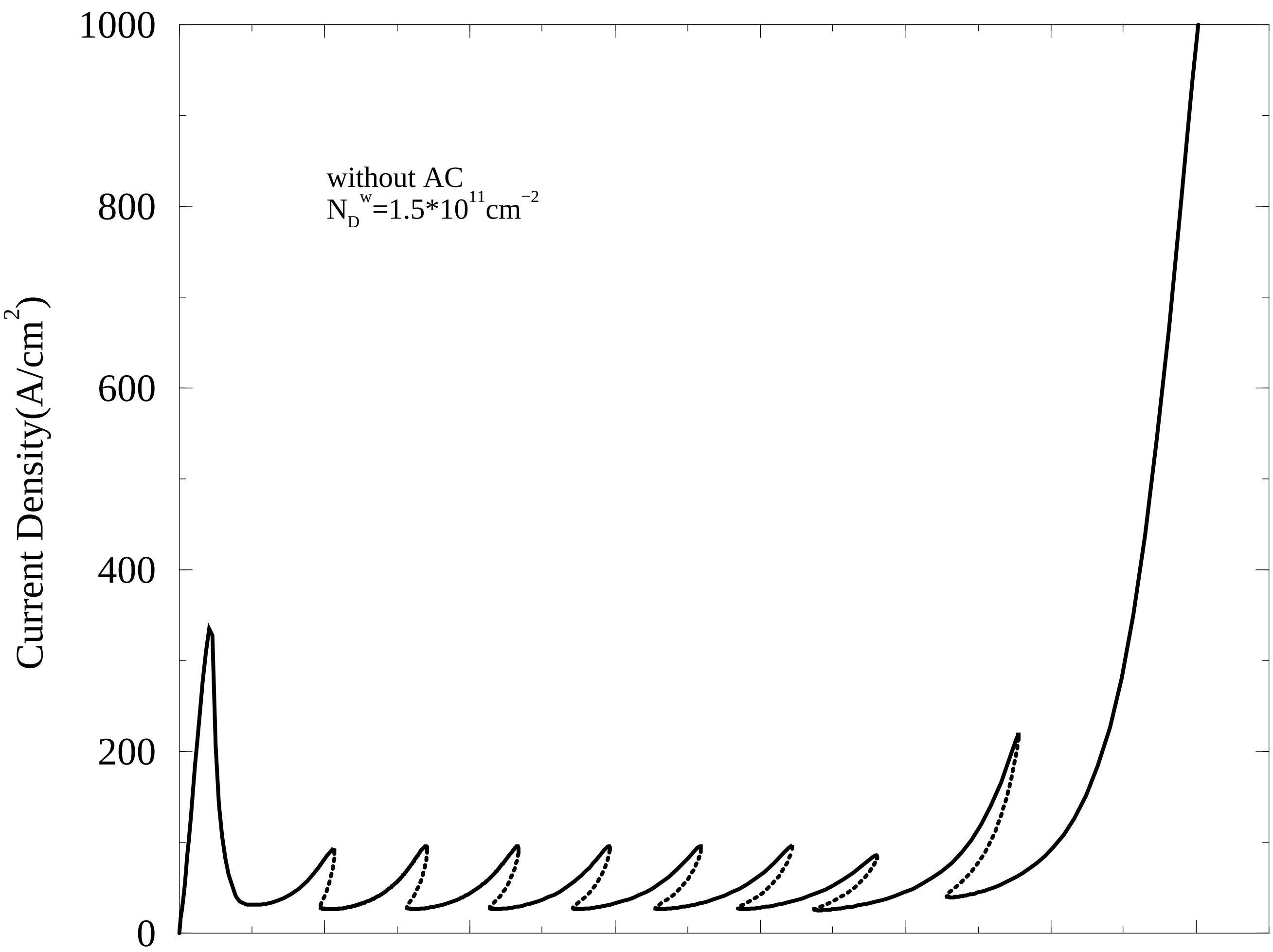
[10] Ramon Aguado, Gloria Platero, Miguel Moscoso and Luis L. Bonilla, Phys. Rev B, **55**, R16053 (1997).

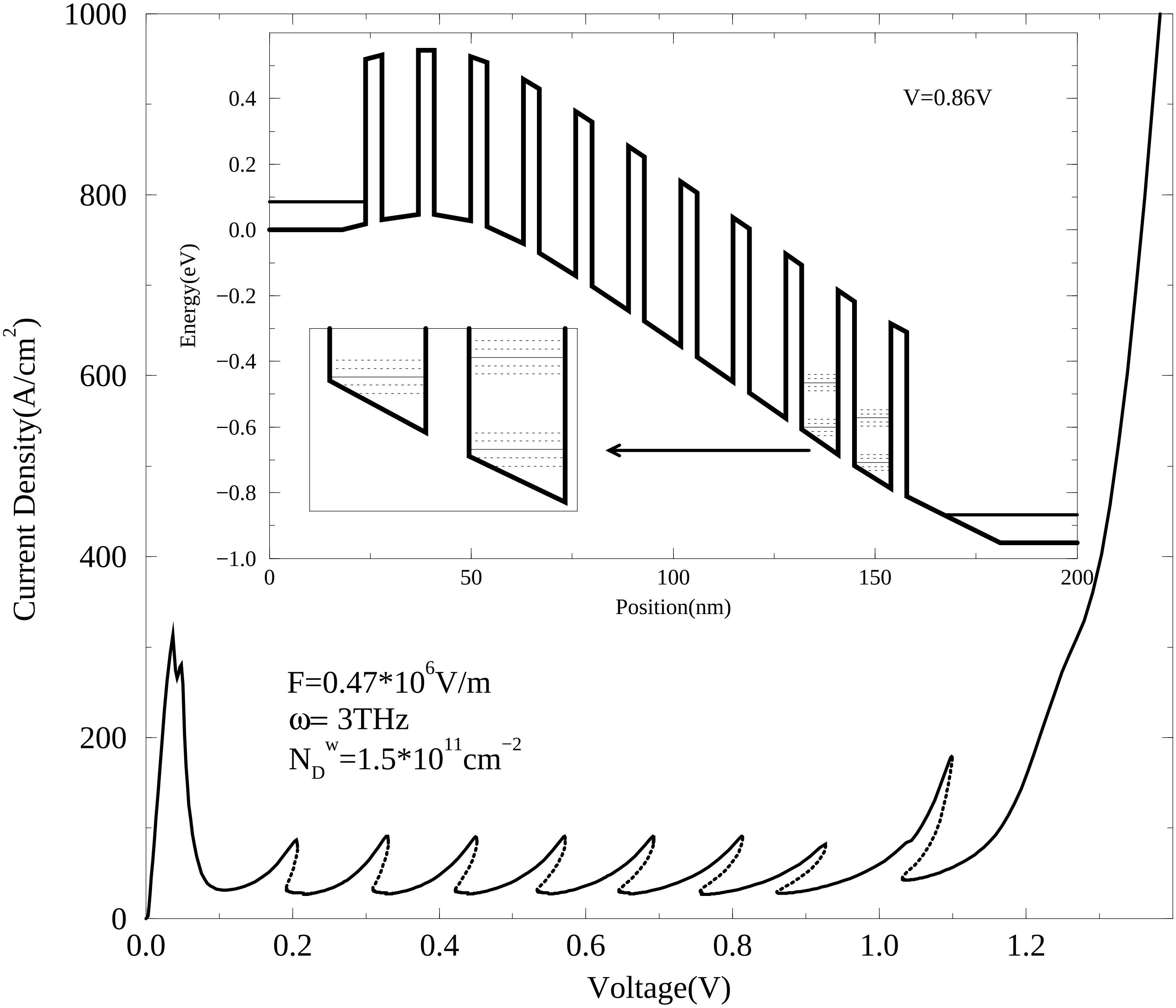
FIGURES

FIG. 1. I–V characteristic for a SL without AC. The continuous (dotted) lines correspond to stable (unstable) solution branches.

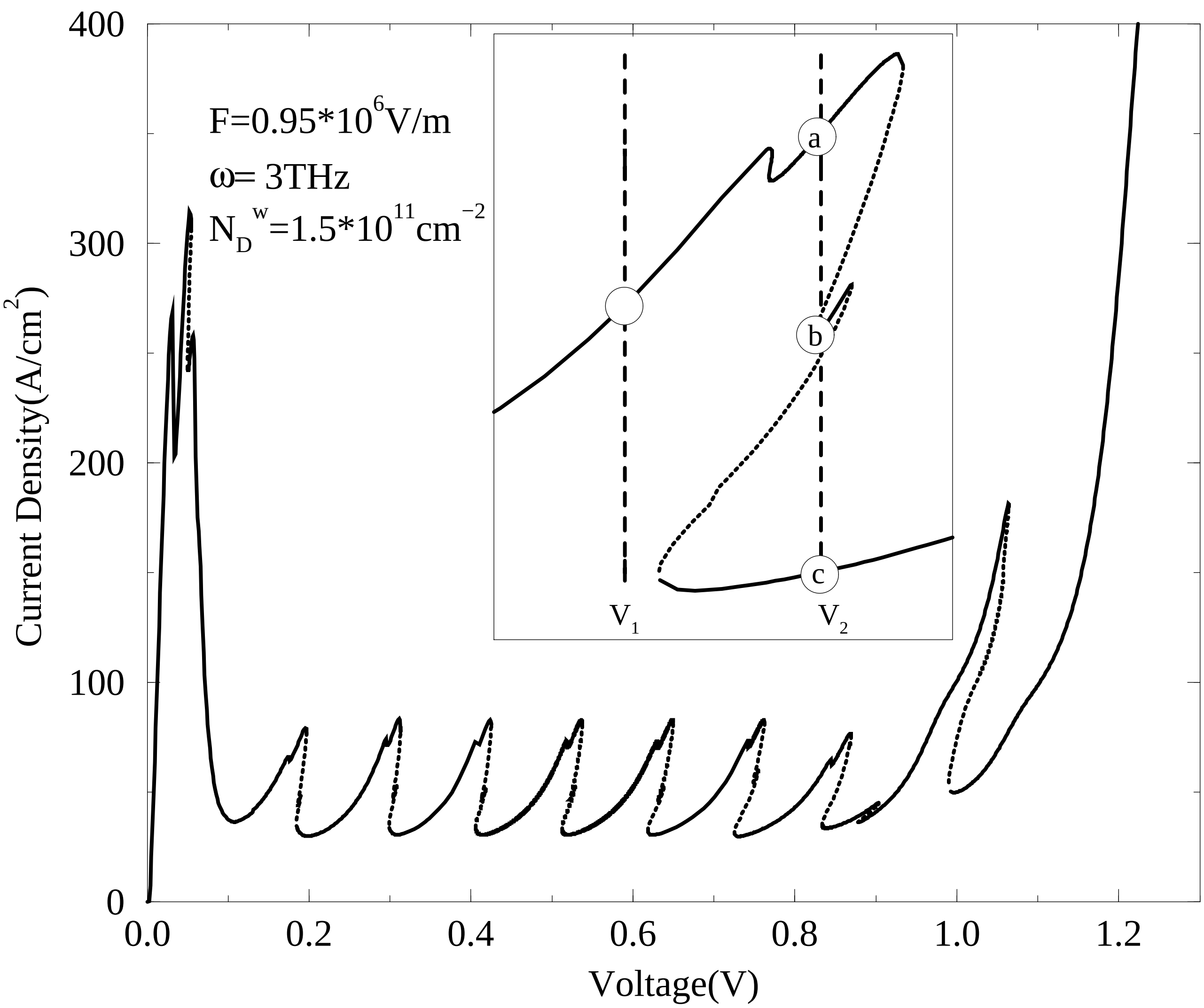
FIG. 2. I–V characteristic for a SL with AC ($F = 0.42 \times 10^6 V/m, \omega = 3THz$).The inset shows the calculated potential profile at V=0.86 V.

FIG. 3. I–V characteristic for a SL with AC ($F = 0.95 \times 10^6 V/m, \omega = 3THz$).The inset shows a blow up of the first branch.


without AC
N_D^w=1.5*10^11cm^-2
Current Density(A/cm^2)
Voltage(V)
0
200
400
600
800
1000
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4



Current Density(A/cm^2)
Voltage(V)
F=0.47*10^{6}V/m
ω= 3THz
N$_D$^{w}=1.5*10^{11}cm^{-2}
Energy(eV)
Position(nm)
V=0.86V



F=0.95*10^6 V/m
ω= 3THz
N_D^w=1.5*10^11 cm^-2
Current Density(A/cm^2)
Voltage(V)
a
b
c
V_1
V_2
0
100
200
300
400
0.0
0.2
0.4
0.6
0.8
1.0
1.2